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This report summarizes work accomplished on the above grant, including publications, participating personnel, and degrees awarded. Of particular note are the results concerning the high field magnetization in Li-Zn ferrite, effects of oxygen firing of polycrystalline Li-ferrite, the effect of substitutions in Li-Co ferrite on the anisotropy and mi-rowave properties, and the understanding of nonlinear microwave processes in ferrites. Some groundwork has also been done on very high frequency (mm wave) material strategies.

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MAGNETIC PROPERTIES OF LITHIUM FERRITE
MICROWAVE MATERIALS

Final Report

U. S. Army Research Office
Grant DAAG29-77-G-0209
Oct. 1, 1977 to Oct. 15, 1980

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Oct. 15, 1980 to April 15, 1982

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ABSTRACT

This report summarizes work accomplished on the above grant, including publications, participating personnel and degrees awarded. Of particular note are the results concerning the high field magnetization in Li-Zn ferrite, effects of oxygen firing of polycrystalline Li-ferrite, the effect of substitutions in Li-Co ferrite on the anisotropy and microwave properties, and the understanding of nonlinear microwave processes in ferrites. Some groundwork has also been done on very high frequency (mm wave) material strategies.

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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I. Results

The six sections of Chapter I summarize (for results already in print) and describe (for results not yet in print) the work accomplished in the following categories and in the publications listed:

A. High Field Magnetization in Zn-Substituted Li-Ferrite

(1) "High Field Magnetization Studies in Lithium Zinc Ferrite", G. O. White, C. A. Edmondson, R. B. Goldfarb and C. E. Patton, J. Appl. Phys. 50, 2381 (1979).

(2) "Magnetic Properties of Lithium Zinc Ferrite", C. E. Patton, C. A. Edmondson and Y. H. Liu, J. Appl. Phys. 53, 2431 (1982).

(3) "Mossbauer Study of Hyperfine Field Distributions and Spin Canting in Lithium Zinc Ferrites", M. Rosenberg, P. Deppe, S. Dey and C. E. Patton (to be published).

(4) "Canting Models for Substituted Magnetic Oxides", C. E. Patton and Y. H. Liu (to be published - to be submitted to Phys. Stat. Solids).

B. Effects of Oxygen Firing of Polycrystalline Li-Ferrite

C. Effect of Substitutions on Relaxation and Anisotropy in Lithium Ferrite

(5) "Microwave Properties of Arc Plasma Sprayed Lithium Ferrite", R. E. Kaelberer, G. O. White and C. E. Patton, J. Physique (France), 38, C1-255 to C1-259 (1977).

(6) Microwave Relaxation Properties of Substituted Lithium Ferrite", C. E. Patton, D. L. Blankenbeckler, C. J. Brower, B. B. Dalton and A. M. Lucero, IEEE Trans. Magnetics 17, 2976 (1981).

(7) "Determination of Anisotropy Field in Polycrystalline Lithium Ferrites", C. J. Brower and C. E. Patton, J. Appl. Phys. 53, 2104 (1982).

(8) "Order-Disorder Effects in the Anisotropy of Substituted Lithium Ferrite", C. J. Brower and C. E. Patton (to be published - submitted to J. Appl. Phys.)

D. Relaxation and Nonlinear Effects

(9) "Influence of the Spin-Wave Linewidth on the Spin-Wave Propagation Direction for Parallel Pumping in Single Crystal YIG", C. E. Patton and W. Jantz, IEEE Trans. Magnetics 14, 698-700 (1978).

(10) "Temperature Dependence of the Parallel-Pump Spin-Wave Linewidth in Porous Yttrium Iron Garnet", G. O. White, C. E. Patton and C. A. Edmondson, J. Appl. Phys. 50, 2118 (1979).

(11) "Spin Wave Instability Theory in Cubic Single Crystal Magnetic Insulators, I. General Theory", C. E. Patton, Phys. Stat. Solidi (b) 92, 211 (1979).

(12) "Spin Wave Instability Theory in Cubic Single Crystal Magnetic Insulators, II. Applications", C. E. Patton, Phys. Stat. Solidi (b) 93, 63 (1979).

(13) "Anomalous Subsidiary Absorption and Evaluation of Spin-Wave Linewidth in Single Crystal YIG", C. E. Patton and W. Jantz, J. Appl. Phys. 50, 7082 (1979).

(14) "High Power Microwave Processes and Parametric Pumping in Single Crystal Ferrites", C. E. Patton, Ferrites - Proceedings of the ICF3, H. Watanabe, S. Iida and M. Sugimoto, eds. (Center for Academic Publications, Japan, 1981), p. 807.

(15) "Spin-Wave Instability Threshold in Single-Crystal Yttrium Iron Garnet for Oblique Pumping", Y. H. Liu and C. E. Patton, J. Appl. Phys. 53 (1982 - in press).

(16) "Spin-Wave Linewidth in Polycrystalline YIG", L. M. Silber and C. E. Patton (to be published - submitted to J. Appl. Phys.)

E. Millimeter Wave Material Strategies

(17) "Magnetoelastic Tuning of the Antiferromagnetic Resonances in Orthoferrites", G. O. White and C. E. Patton, IEEE Trans. Magnetics 16, 684 (1980).

(18) "Foldover Effect in Ferromagnetic Resonance in a Planar Hexagonal Ferrite", L. M. Silber and C. E. Patton (work still in progress, eventual publication in J. Appl. Phys. likely).

F. Instrumentation

(19) "Simple Analytic Method for Microwave Cavity Q Determination", Z. Frait and C. E. Patton, Rev. Sci. Instrum. 51, 1092 (1980).

(20) "Methods for the Grinding and Polishing of Sphere Samples", J. N. Paranto and C. E. Patton, Rev. Sci. Instrum. 52, 262 (1981).

(21) "Temperature Finger for 77 K to 350 C", C. J. Brower and G. O. White (to be submitted to Rev. Sci. Instrum.)

(22) High Power Semi-Automated Microwave Spectrometer for Spin-Wave Instability Studies", C. J. Brower, G. O. White and C. E. Patton.

G. Reviews

(23) "Magnetic Properties of Lithium Ferrite Microwave Materials", G. O. White and C. E. Patton, J. Magn. Mag. Materials 9, 299 (1978).

I. A. High Field Magnetization in Zn-Substituted Li-Ferrite

Zinc enters A-sites, so that small levels of substitution cause the spontaneous magnetization to increase. Zinc levels above about 0.3 at./F.U. cause the moment to decrease, due to a canting of B-site iron precipitated by a dilution of the intrasublattice exchange field. Publications (1) to (4) address the details of the magnetic interactions which lead to this canting. A fully localized, self-consistent iterative model has been developed (4), but even this scheme does not adequately fit the experimental data. A fit may be obtained by treating the exchange "constants" as adjustable parameters. J_{AB} appears, from this, to decrease with increasing zinc. The Mossbauer data (3) show discrete local environment effects.

B. Effects of Oxygen Firing of Polycrystalline Li-Ferrite

These results were reported in the semiannual progress report, Oct. 1, 1977 to July 31, 1978. The basic result was that firing in oxygen at 5 and 10 atm for 10 hours reduced the dc conductivity to 3×10^{-7} and 5.6×10^{-8} $(\Omega\text{-cm})^{-1}$, respectively. These figures are orders of magnitude smaller than reported for 1 atm. firings. Further work was anticipated but did not materialize due to Dr. White's departure to private industry.

C. Effects of Substitutions on Relaxation and Anisotropy in Lithium Ferrite

Publication (5) reported results on effective and spin-wave linewidth in Li-ferrite prepared by Dr. Richard Babbit, Army

Electronics Command by the arc-plasma-spray technique and showed that APS materials have relaxation properties as good or better than conventionally prepared Li-ferrite.

Publication (6) reports extensive effective and spin-wave linewidth data on Li-ferrite with Co, Mn, Ti, Ni and Al substitutions, and various combinations thereof. It is basically a catalog of relaxation vs. substitution, a (hopefully) useful reference for Li-ferrite users.

Publications (7) and (8) summarize approximately 2/3 of the Ph.D. thesis results of C. J. Brower. A novel technique, involving measurements of ferromagnetic resonance vs. frequency and temperature is used to determine the magnetocrystalline anisotropy vs. temperature for polycrystalline, wide linewidth Li-ferrite with Co, Mn and Ti. Publication (8) shows that the role of cobalt as an anisotropy compensator depends critically on effects related to atomic ordering, including migration to A-sites and oxidation by manganese.

D. Relaxation and Nonlinear Effects

The six publications in this category concern the physics of relaxation. The experimental studies were carried out on polycrystalline YIG, for which a nice series of samples with microstructure variations (porosity and grain size) were available, and on narrow linewidth single crystals. No Li-ferrite counterparts were available. The results do impact Li-ferrite relaxation mechanisms, and are therefore relevant to this program. Publications (9) through (15) address the problem of instability effects

induced by the wave-vector $\bar{k}$-dependence of the spin-wave linewidth. The interactions appear to cause interesting spin-wave switching effects (e.g., a beam of spin-waves switches direction) with possible device applications. Publication (10) addresses the origin of the spin-wave linewidth (and hence device peak power capability) due to microstructure considerations. An additional publication on relaxation in polycrystals due to porosity scattering is anticipated, based on C. J. Brower's thesis work in progress.

E. Millimeter Wave Strategies

As outlined in the 1980 renewal proposal, a growing ARO interest in magnetic materials for application in the millimeter regime prompted us to look at a number of possible strategies. Publication (17) addresses the possible use of stress to downtune the natural antiferromagnetic resonances in orthoferrites to useful frequencies. While conclusions on practicality would be premature, the improving LPE technology for growing magnetic oxide thin films may hold promise for stress tuning. In the course of work on some hexagonal ferrites provided by Dr. Arthur Tauber, Army Electronics Command, a peculiar very low power nonlinear effect was observed in FMR at levels on the order of mW. This could have detrimental implications for some device applications. The effect is not understood, and further work is continuing (unfunded).

F. Instrumentation

A number of spin-off instrumentation developments have been generated during the course of the program. We developed an analytic, precise method for cavity-Q determination, perfected

methods for producing very high surface polish on ferrite spheres, designed a wide-temperature diamond finger to hold samples for microwave work, and upgraded the semi-automated high power spectrometer to deliver pulses synchronized to the 800 Hz power supply.

G. Reviews

The original proposal served as the text (with some modification) for an invited review article in the Journal of Magnetism and Magnetic Materials.

II. Personnel

The personnel supported on t · ·.ject in one form or another (salary, materials, etc.) are listed below.

Principal Investigator:	Carl E. Patton Professor of Physics
Co-Investigator:	Geoffrey O. White Assistant Professor Ph.D., Stanford University Present Employer, Boeing Company
Visiting Research Fellow:	Y. H. Liu, Shandong University, PRC
Visiting Professor:	Leo M. Silber Polytechnical Institute of New York
Ph.D. Candidate:	Charles J. Brower Ph.D. to be completed by 9/1/82 Future employer: Verbatim Corp.
Ph.D. Candidate:	Charles A. Edmondson Ph.D. research complete, thesis writing and defense to be completed in due course. Present employer: United States Navy (Nuclear Submarine Officer)
Ph.D. Candidate:	William Wilber Ph.D. research shifted to separate ARO/NSF funded project. Due to complete Ph.D. in 1984.

<u>Other Personnel</u> (hourly, workstudy, etc.):

Undergraduate Students:

Clinton Seanor, B.S. in Geology
M.S. in progress

Benjamin Dalton, Electrical Engineering Major

Joe Paranto, B.S. in Physics

Greg Sandoval, Chemistry Major

Kathy Anderson, Physics Major

David Blankenbeckler, Electrical Engineering Major

Scott Pay, Major unknown

Jim O'Connell, Engineering Major

Dennis Garcia, B.S. in Engineering

George Hagar, Major in Engineering

Fred Maes, Physics Major

High School Students (ARO-REAP Program):

Andy Lucero

Juanita Olivas

Saraz Naqui

Junior High School Students (CETA Program)

Bob Clarke

Dale Lippert

TOTAL PERSONNEL: 23